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On the Salecker-Wigner limit and the use of interferometers in space-time-foam studies

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ABSTRACT

The recent paper gr-qc/9909017 criticizes the limit on the measurability of distances that was derived by Salecker and Wigner in the 1950s. If justified, this criticism would have important implications for all the recent studies that have used in various ways the celebrated Salecker-Wigner result, but I show here that the analysis reported in gr-qc/9909017 is incorrect. Whereas Salecker and Wigner sought an operative definition of distances suitable for the Planck regime, the analysis in gr-qc/9909017 relies on several assumptions that appear to be natural in the context of most present-day experiments but are not even meaningful in the Planck regime. Moreover, contrary to the claim made in gr-qc/9909017, a relevant quantum uncertainty which is used in the Salecker-Wigner derivation cannot be truly eliminated; unsurprisingly, it can only be traded for another comparable contribution to the total uncertainty in the measurement. I also comment on the role played by the Salecker-Wigner limit in my recent proposal of interferometry-based tests of quantum properties of space-time, which was incorrectly described in gr-qc/9909017. In particular, I emphasize that, as discussed in detail in gr-qc/9903080, only some of the quantum-gravity ideas that can be probed with modern interferometers are motivated by the Salecker-Wigner limit. The bulk of the insight we can expect from such interferometric studies concerns the properties of "foamy" models of space-time, which are intrinsically interesting independently of the Salecker-Wigner limit.

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1 INTRODUCTION

In the recent paper [1], Adler, Nemenman, Overduin and Santiago criticize a limit on the measurability of distances which was originally derived by Salecker and Wigner in the 1950s [2]. If correct, this criticism would have implications for all the recent papers which have used in one way or another the celebrated Salecker-Wigner study. In particular, some of quantum-gravity ideas that can be tested using the interferometry-based experiments I proposed in Refs. [3, 4] are motivated by the Salecker-Wigner limit; moreover, the Salecker-Wigner limit is the common ingredient (even though this ingredient was used in very different ways and from very different viewpoints [4, 5]) of several recent studies concerning possible limitations on the measurability of distances [5, 6, 7] or limitations in the "tightness" achievable [8] in the operative definition of a network of geodesics.

I show here that the analysis reported in Ref. [1] is incorrect. It relies on assumptions which cannot be justified in the framework set up by Salecker and Wigner (while the same assumptions would be reasonable in the context of certain measurements using rudimentary experimental setups). In particular, contrary to the claim made in Ref. [1], the source of $\sqrt{T_{obs}}$ uncertainty (with T_{obs} denoting the time of observation in a sense which will be clarified in the following) that was considered by Salecker and Wigner cannot be truly eliminated; unsurprisingly, it can only be traded for another source of $\sqrt{T_{obs}}$ uncertainty. The analysis reported in Ref. [1] also handles inadequately the idealized concept of "clock" relevant for the type of "in-principle analysis" discussed by Salecker and Wigner.

In addition to this incorrect criticism of the limit derived by Salecker and Wigner, Ref. [1] also misrepresented the role of the Salecker-Wigner limit in providing motivation for the mentioned proposal [3, 4] of interferometry-based space-time-foam studies. The reader unfamiliar with the relevant literature would come out of reading Ref. [1] with the impression that such interferometry-based tests could only be sensitive to quantum-gravity ideas motivated by the Salecker-Wigner limit; instead[2] only some of the quantum-gravity ideas that can be probed with modern interferometers are motivated by the Salecker-Wigner limit. The bulk of the insight we can expect from such interferometric studies concerns the stochastic properties of "foamy" models of space-time, which are intrinsically interesting independently of the Salecker-Wigner limit.

I shall articulate this Letter in sections, each making one conceptually-independent and simple point. I start in the next Section 2 by reviewing which type of ideas concerning stochastic properties of "foamy" models of space-time can be tested with modern interferometers. From the discussion it will be clear that interest in these "foamy" models of space-time is justified quite independently of the Salecker-Wigner limit (in fact, this limit will not even be mentioned in Section 2). Section 2 is perhaps the most important part of this Letter, since its primary objective is the one of making sure that experimentalists do not loose interest in the proposed interferometry-based tests as a result of the confusion generated by Ref. [1].

The remaining sections do concern the Salecker-Wigner limit, reviewing some relevant results and clarifying various incorrect statements provided in Ref. [1]. Section 3 briefly reviews the argument put forward by Salecker and Wigner. Section 4 emphasizes that the Salecker-Wigner limit is obtained in ordinary quantum mechanics, but it can provide motivation for a certain type of ideas concerning quantum properties of space-time. The nature of the idealized clock relevant for the type of analysis performed by Salecker and Wigner is discussed in Section 5, also clarifying in which sense some comments on this clock that were made in Ref. [1] are incorrect. Section 6 clarifies how the potential well considered in Ref. [1] would simply trade one source of $\sqrt{T_{obs}}$ uncertainty for another source of $\sqrt{T_{obs}}$ uncertainty. In Section 7 I clarify that the comments on decoherence of the clock presented

[2] This was already discussed in detail in Ref. [4] which appeared six moths before Ref. [1] but was not mentioned (or taken into account in any other way) in Ref. [1].

in Ref. [1] would not apply to the Salecker-Wigner setup. Section 8 is devoted to some closing remarks.

2 FOAMY SPACE-TIME AND MODERN INTERFEROMETERS

A prediction of nearly all approaches to the unification of gravitation and quantum mechanics is that at very short distances the sharp classical concept of space-time should give way to a somewhat "fuzzy" (or "foamy") picture, possibly involving virulent geometry fluctuations (sometimes intuitively/heuristically associated with virtual black holes and wormholes). This subject originates from observations made by Wheeler [9] and Hawking [10] and has developed into a rather vast literature. Examples of recent proposals in this area (and good starting points for a literature search) can be found in Refs. [11, 12, 13, 14, 15, 16], which explored possible implementations/consequences of space-time foam ideas in various versions of quantum gravity, and in Refs.[17, 18, 19], which performed similar studies in an approach based on non-critical strings. Although the idea of space-time foam appears to have significantly different incarnations in different quantum-gravity approaches, a general expectation that emerges from this framework is that the distance between two bodies "immerged" in the space-time foam would be affected by (quantum-gravity-induced) fluctuations.

A phenomenological model of fluctuations affecting a quantum-gravity distance must describe the underlying stochastic processes. As explained in detail in Refs. [4, 20], from the point of view of comparison with data obtainable with modern interferometers the best way to characterize such models is through the associated amplitude spectral density of distance fluctuations [21, 22]. A natural starting point for the parametrization of this amplitude spectral density is given by[3]

$$S(f) = f^{-\beta} \left(\mathcal{L}_\beta\right)^{\frac{3}{2}-\beta} c^{\beta-\frac{1}{2}} \ , \tag{1}$$

where c is the speed-of-light constant, the dimensionless parameter β carries the information on the nature of the underlying stochastic processes and the dimensionful (length) parameter $\mathcal{L}_\beta$ carries the information on the magnitude and rate of the fluctuations[4]. A detailed discussion of the definition and applications of this type of amplitude spectral density can be found in Ref. [21, 22]. For the readers unfamiliar with the use of amplitude spectral densities some useful intuition can be obtained from the fact that [21, 23] the standard deviation of the fluctuations is formally related to $S(f)$ by

$$\sigma^2 = \int_{1/T_{obs}}^{f_{max}} [S(f)]^2 \, df \ , \tag{2}$$

where T_{obs} is the time over which the distance is kept under observation.

In Eq. (1) the parameter β could in principle take any value, and it is even quite plausible that in reality the stochastic processes (if at all present) would have a more complex structure than the simple power law codified in Eq. (1). Still, Eq. (1) appears to be the

[3]Of course, a parametrization such as the one in Eq. (1) could only be valid for frequencies f significantly smaller than the Planck frequency c/L_p and significantly larger than the inverse of the time scale over which the classical geometry of the space-time region where the experiment is performed manifests significant curvature effects.

[4]I am assigning an index β to $\mathcal{L}_\beta$ just in order to facilitate a concise description of experimental bounds. For example, if data were to rule out the fluctuations scenario with, say, $\beta = 0.6$ for all values of the effective length scale down to, say, $10^{-27}m$ one could simply write the formula $\mathcal{L}_{\beta=0.6} < 10^{-27}m$.

natural starting point for a phenomenological programme of exploration of the possibility of "distance-fuzziness" effects induced by quantum properties of space-time. In particular, it seems natural to devote special attention to values of β in the range $1/2 \leq \beta \leq 1$; in fact, as explained in greater detail in Refs. [4], $\beta = 1/2$ is the type of behaviour one would expect [24] in fuzzy space-times without quantum decoherence (without "information loss"), while the case $\beta = 1$ provides the simplest model of stochastic (quantum) fluctuations of distances, in which a distance is affected by completely random minute (possibly Planck-length size) fluctuations which can be modeled as stochastic processes of random-walk type. Values of β somewhere in between the cases $\beta = 1/2$ and $\beta = 1$ could provide a rough model of space-times with decoherence effects somewhat milder than the $\beta = 1$ random-walk case. In other words, in light of the realization [4, 24] that foamy space-times without decoherence would only be consistent with distance fluctuations of type $\beta = 1/2$ the popular arguments that support quantum-gravity-induced deviations from quantum coherence motivate interest in values of β somewhat different from 1/2.

Readers unfamiliar with the subject can get an intuitive picture of the relation between the value of β and decoherence by resorting again to Eq. (2). For example, as discussed in greater detail in Ref. [4, 23], the case $\beta = 1$ corresponds to $\sigma \sim \sqrt{T_{obs}}$, the standard deviation characteristic of random-walk processes, and this type of T_{obs}-dependence would be consistent with decoherence in the sense that the information stored in a network of distances would degrade over time[5]. Similar observations, but with weaker power-law dependence on T_{obs}, hold for values of β in the range $1/2 < \beta < 1$. In the limiting case $\beta = 1/2$ the T_{obs}-dependence turns from power-law to logarythmic, and this is of course the closest one can get to modeling space-times without intrinsic decoherence (*i.e.* such that the associated standard deviation is T_{obs}-independent) within the parametrization set up in Eq. (1)[6].

As observed in Ref. [4], independent support for a fuzzy picture of space-time of the type here being considered comes from recent studies [18, 14, 15, 16, 19] suggesting that space-time foam might induced a deformation of the dispersion relation that characterizes the propagation of the massless particles used as space-time probes in the operative definition of distances. Such a deformation of the dispersion relation would affect [18, 14, 4] the measurability of distances just in the way expected for a fuzzy picture of space-time of the type here being considered.

In general the connection between loss of quantum coherence and a foamy/fuzzy picture of space-time is very deep and has been discussed in numerous publications (a sample of recent ideas in this area can be found in Refs. [6, 12, 26, 27, 28]). However, while a substantial amount of work has been devoted to the "physics case" for quantum-gravity induced decoherence, enormous difficulties have been encountered in developing a satisfactory formalism for this type of quantum gravity. The primary obstruction for the search of the correct decoherence-encoding formalism is the fact that a new mechanics would be needed (ordinary quantum mechanics evolves pure states into pure states) and the identification of such a new mechanics in the absence of any guidance from experiments is extremely hard. It is in this context that a phenomenology based on the parametrization (1) finds its motivation. When

[5]For example, an observer could store "information" in a network of bodies by adjusting their distances to given values at a given initial time. If space-time did involve distance fluctuations with standard deviation that grows with the time of observation, there would be an intrinsic mechanism for this information to degrade over time. Other intuitive descriptions of the relation between certain fuzzy space-times and decoherence can be found in Ref. [6]. Depending on the reader's background it might also be useful to adopt the language of the "memory effect", as done, for example, in Ref. [25].

[6]As explained in Refs. [3, 4] and reviewed here below, we are still very far from being able to test the type fuzziness one might expect for space-times without decoherence. It is therefore at present quite sufficient to model this type of fuzziness by taking $\beta = 1/2$ in (1). Readers with an academic interest in seeing a more complete description of stochastic processes plausible for a space-time without decoherence can consult Ref. [24].

a satisfactory workable formalism implementing the intuition on quantum-gravity-induced decoherence becomes available, we will be in a position to extract from it a specific form of the stochastic processes characterizing the associated foamy space-time, with a definite prediction for $S(f)$. While waiting for these developments on the theoretical-physics side we might get some help from experiments; in fact, as observed in Refs. [3, 4], the remarkable sensitivity of modern interferometers (the ones whose primary objective is the detection of the classical-gravity phenomenon of gravity waves [22]) allows us to put significant bounds on the parameters of Eq. (1). While it is remarkable that some candidate quantum-gravity phenomena are within reach of doable experiments, it is instead quite obvious that interferometers would be the natural in-principle tools for the study of distance fluctuations. In fact, the operation of interferometers is based on the detection of minute changes in the positions of some test masses (relative to the position of a beam splitter), and, if these positions were affected by quantum fluctuations of the type discussed above, the operation of interferometers would effectively involve an additional source of noise due to quantum gravity [3, 4].

The data obtained at the *Caltech 40-meter interferometer*, which in particular achieved [29] displacement noise levels with amplitude spectral density of about $3 \cdot 10^{-19} m/\sqrt{Hz}$ in the neighborhood of 450 Hz, allow us to set the bound [3, 4, 20]

$$[\mathcal{L}_\beta]_{Caltech} < \left[\frac{3 \cdot 10^{-19} m}{\sqrt{Hz}} (450 Hz)^\beta \, c^{(1-2\beta)/2} \right]^{2/(3-2\beta)} . \qquad (3)$$

In order to get some intuition for the significance of this bound let us consider the case $\beta = 1$. For $\beta = 1$ the bound in Eq. (3) takes the form $L_{\beta=1} < 10^{-40} m$. This is quite impressive since $\beta = 1$, $L_{\beta=1} \sim 10^{-35} m$ corresponds to fluctuations in the 40-meter arms of the Caltech interferometer that are of Planck-length magnitude ($L_p \sim 10^{-35} m$) and occur at a rate of one per each Planck-time interval ($t_p = L_p/c \sim 10^{-44} s$). The data obtained at the *Caltech 40-meter interferometer* therefore rule out this simple model in spite of the minuteness (Planck-length!!) of the fluctuations involved. Another intuition-building observation concerning the significance of this result is obtained by considering the standard deviation $\sigma \sim \sqrt{L_p c T_{obs}}$ which would correspond to such Planck-length fluctuations occurring at $1/t_p$ rate. From $\sigma \sim \sqrt{L_p c T_{obs}}$ one predicts fluctuations with standard deviation even smaller than $10^{-5} m$ on a time of observation as large as 10^{10} years (the size of the whole observable universe is about 10^{10} light years!!) but in spite of their minuteness these can be ruled out exploiting the remarkable sensitivity of modern interferometers.

Additional comments on values of β in the range $1/2 < \beta < 1$ can be found in Refs. [4, 20] (in Ref. [4] the reader will find a detailed discussion of the case $\beta = 5/6$). In the present Letter it suffices to observe that the bound encoded in Eq. (3) becomes less stringent as the value of β decreases. In particular, in the limit $\beta = 1/2$, the case providing an effective model for space-times without intrinsic decoherence, Eq. (3) only implies $\mathcal{L}_{\beta=1/2} < 10^{-17} m$, which is still very comfortably consistent with the natural expectation [24] that within that framework one would have $\mathcal{L}_{\beta=1/2} \sim L_p \sim 10^{-35} m$.

In this section I have in no way considered the statements on the Salecker-Wigner limit reported in Ref. [1]. As anticipated in the Introduction, I have opened the paper with this section briefly summarizing the status of interferometry-based studies of distance fuzziness. The fact that the Salecker-Wigner limit was not even mentioned in this section should however clarify that, contrary to the impression one gets from reading Ref. [1], these interferometric studies are intrinsically interesting, quite independently of any consideration concerning the Salecker-Wigner limit. This is already clear at least to a portion of the community; for example, in recent work [19] on foamy space-times (without any reference to the

Salecker-Wigner related literature) the type of modern-interferometer sensitivity exposed in Refs. [3, 4] was used to constrain certain novel candidate light-cone-broadening effects .

The brief review provided in this section should also clarify in which sense another statement provided in Ref. [1] is misleading. It was in fact stated in Ref. [1] that, since the sensitivity of modern interferometers is at the level[7] of $10^{-18}m$, any quantum-gravity model tested by such interferometers should predict a break down of the classical space-time picture on distance scales of order $10^{-18}m$. Let me illustrate in which sense this statement misses the substance of the proposed tests by taking again as an example the one with $\beta = 1$, which allows an intuitive discussion in terms of simple random-walk processes. We have seen that this can describe fluctuations of Planck-length magnitude occurring at $1/t_p$ rate. All the scales involved in the stochastic picture are at the $10^{-35}m$ scale, but we can rule out this scenario using a "$10^{-18}m$ machine" because this machine operates at frequencies of order a few hundred Hz (which correspond to time scales of order a few milliseconds) and therefore is effectively sensitive to the collective effect of a very large number of minute Planck-scale effects (*e.g.*, in the simple random-walk case, during a time of a few milliseconds as many as 10^{41} Planck-length fluctuations would affect the arms of the interferometer). This is not different from other similar experiments probing fundamental physics. For example, proton-decay experiments use protons at rest (objects of size $10^{-16}m$) to probe physics on distance scales of order $10^{-32}m$ (the conjectured size of gauge bosons mediating proton decay), and this is done by monitoring a very large number of protons so that the apparatus is sensitive to a collective effect which is much larger than the decay probability of each individual proton. A similar idea has already been exploited in "quantum-gravity phenomenology" [20]; in fact, the experiment proposed in Ref. [14] is possible only because the photons that reach us from distant astrophysical sources have traveled for such a long time that they are in principle sensitive to the collective effect of a very large number of interactions with the space-time foam.

3 THE SALECKER-WIGNER LIMIT IN ORDINARY QUANTUM MECHANICS

Having clarified what part of the motivation for interferometric studies is completely independent of the Salecker-Wigner limit I have two remaining tasks: the one of providing a brief review of the Salecker-Wigner limit and the one of correcting the incorrect statements on the Salecker-Wigner limit which were given in Ref. [1]. Let me start by considering the original Salecker-Wigner limit within ordinary quantum mechanics. The analysis reported by Salecker and Wigner in Ref. [2] concerns the measurability of distances. In particular, they considered the measurement of the distances defined by the network of free-falling bodies that might compose an idealized "material reference system" [32]. Those who have been developing the research line started by Salecker and Wigner have also considered more general distance measurements, but the emphasis has remained on measurement analyses that might provide intuition on the way in which distances could be in principle operatively defined in quantum gravity. The essence of the Salecker-Wigner argument can be summarized as follows. They "measured" (in the "*gedanken*" sense) the distance D between two bodies by exchanging a light signal between them. The measurement procedure requires *attaching*[8]

[7]For example, planned interferometers [30, 31] with arm lengths of a few Km expect to detect gravity waves of amplitude as low as $3 \cdot 10^{-22}$ (at frequencies of about $100Hz$). This roughly means that these modern gravity-wave interferometers should monitor the (relative) positions of their test masses (the beam splitter and the mirrors) with an accuracy of order $10^{-18}m$.

[8]Of course, for consistency with causality, in such contexts one assumes devices to be "attached non-rigidly," and, in particular, the relative position and velocity of their centers of mass continue to satisfy the

a light-gun (*i.e.* a device capable of sending a light signal when triggered), a detector and a clock to one of the two bodies and *attaching* a mirror to the other body. By measuring the time T_{obs} (time of observation) needed by the light signal for a two-way journey between the bodies one also obtains a measurement of the distance D. For example, in flat space and neglecting quantum effects one simply finds that $D = cT_{obs}/2$. Unlike most conventional measurement analyses, Salecker and Wigner were concerned with the quantum properties of the devices involved in the measurement procedure. In particular, since they were considering a distance measurement, it was clear that quantum uncertainties in the position (relative to, say, the center of mass of the two bodies whose distance is being measured) of some of the devices involved in the measurement procedure would translate into uncertainties in the overall measurement of D. Importantly, the analysis of these device-induced uncertainties leads to a lower bound on the measurability of D. To see this it is sufficient to consider the contribution to δD coming from only one of the quantum uncertainties that affect the motion of the devices. In Ref. [2] (and in the more recent studies reported in Refs. [6, 8]) the analysis focused on the uncertainty in the position of the Salecker-Wigner clock, while in some of my related studies [5, 7] the analysis focused on the uncertainties that affect the motion of the center of mass of the system composed by the light-gun, the detector and the clock. These approaches are actually identical, since (as I shall discuss in greater detail later) the Salecker-Wigner clock is conceptualized [2] as a device not only capable of keeping track of time but also capable of sending and receiving signals; it is therefore a composite device including at least a clock, a transmitter and a receiver. Moreover, the substance of the argument does not depend very sensitively on which position is considered, as long as it is associated with a device whose position must be known over the whole time required by the measurement procedure. For definiteness, let me here proceed denoting with x^* and v^* the position and the velocity of an idealized Salecker-Wigner clock. Assuming that the experimentalists prepare this device in a state characterised by uncertainties δx^* and δv^*, one easily finds [2, 5, 6, 7]

$$\delta D \geq \delta x^* + T_{obs} \delta v^* \geq \delta x^* + \left(\frac{1}{M_b} + \frac{1}{M_d} \right) \frac{\hbar T_{obs}}{2\, \delta x^*} \,, \tag{4}$$

where M_b is the sum of the masses of the two bodies whose distance is being measured, M_d is the mass of the device being considered (*e.g.*, the mass of the clock) and I also used the fact that Heisenberg's *Uncertainty Principle* implies $\delta x^* \delta v^* \geq (1/M_b + 1/M_d)\hbar/2$. [The *reduced mass* $(1/M_b + 1/M_d)^{-1}$ is relevant for the relative motion of the clock with respect to the position of the center of mass of the system composed by the two bodies whose distance is being measured.]

Evidently, from (4) it follows that for given M_b and M_d there is a lower bound on the measurability of D

$$\delta D \geq \sqrt{\frac{\hbar T_{obs}}{2} \left(\frac{1}{M_b} + \frac{1}{M_d} \right)} \,. \tag{5}$$

The result (5) may at first appear somewhat puzzling, since ordinary quantum mechanics should not limit the measurability of any given observable. [It only limits the combined measurability of pairs of conjugate observables.] However, from a physical/phenomenological and conceptual viewpoint it is well understood that the proper framework for the application of the formalism of quantum mechanics is the description of the results of measurements performed by classical devices (devices that can be treated as approximately classical within the level of accuracy required by the measurement). It is therefore not surprising that

standard uncertainty relations of quantum mechanics.

the infinite-mass (classical-device[9]) limit turns out to be required in order to bridge the gap between (5) and the prediction $min\delta D = 0$ of the formalism of ordinary quantum mechanics.[10]

In this section on the Salecker-Wigner limit I have not taken into account the gravitational properties of the devices. It has been strictly confined within ordinary (non-gravitational) quantum mechanics. Actually, one can interpret the Salecker-Wigner limit as one way to render manifest the true nature of the physical applications of the quantum-mechanics formalism and its relation with a certain class of experiments (the ones performed by classical devices). The picture emerging from the analysis of Salecker and Wigner fits well within a general picture emerging from other similar studies. In particular, the celebrated Bohr-Rosenfeld analysis [33] of the measurability of the electromagnetic field found that the accuracy allowed by the formalism of ordinary quantum mechanics could only be achieved using a very special type of device: idealized test particles with vanishing ratio between electric charge and inertial mass.

4 FROM THE SALECKER-WIGNER LIMIT TO QUANTUM GRAVITY

Let me now take the Salecker-Wigner limit as starting point for a quantum-gravity argument. I will therefore now not only consider the quantum properties of the devices, but also their gravitational properties. It is well understood (see, *e.g.*, Refs. [5, 7, 8, 34, 35, 36]) that the combination of the gravitational properties and the quantum properties of devices can have an important role in the analysis of the operative definition of gravitational observables. Actually, by ignoring the way in which the gravitational properties and the quantum properties of devices combine in measurements of geometry-related physical properties of a system one misses some of the fundamental elements of novelty we should expect for the interplay of gravitation and quantum mechanics; in fact, one would be missing an element of novelty which is deeply associated with the Equivalence Principle. For example, attempts to generalize the mentioned Bohr-Rosenfeld analysis to the study of gravitational fields (see, *e.g.*, Ref. [34]) are of course confronted with the fact that the ratio between gravitational "charge" (mass) and inertial mass is fixed by the Equivalence Principle. While ideal devices with vanishing ratio between electric charge and inertial mass can be considered at least in principle, devices with vanishing ratio between gravitational mass and inertial mass are not admissible in any (however formal) limit of the laws of gravitation. This observation provides one of the strongest elements in support of the idea [7] that the mechanics on which quantum gravity is based must not be exactly the one of ordinary quantum mechanics. In turn this contributes to the whole spectrum of arguments that support the expectation that the loss of quantum coherence might be intrinsic in quantum gravity.

Similar support for quantum-gravity-induced decoherence emerges from taking into account both gravitational and quantum properties of devices in the analysis of the Salecker-Wigner measurement procedure. The conflict with ordinary quantum mechanics immediately

[9] A rigorous definition of a "classical device" is beyond the scope of this Letter. However, it should be emphasized that the experimental setups being here considered require the devices to be accurately positioned during the time needed for the measurement, and therefore an ideal/classical device should be infinitely massive so that the experimentalists can prepare it in a state with $\delta x \, \delta v \sim \hbar/M \sim 0$.

[10] Perhaps more troubling is the fact that $min\delta D = 0$ appears to require not only an infinitely large M_d but also an infinitely large M_b. One feels somewhat uncomfortable treating the mass of the bodies whose distance is being measured as a parameter of the apparatus. This might be another pointer to the fact that quantum measurement of gravitational/geometric observables requires a novel conceptualization of quantum mechanics. I postpone the consideration of this point to future work.

arises because the infinite-mass limit is in principle inadmissible for measurements concerning gravitational effects. As the devices get more and more massive they increasingly disturb the gravitational/geometrical observables, and well before reaching the infinite-mass limit the procedures for the measurement of gravitational observables cannot be meaningfully performed [5, 6, 7]. These observations, which render unaccessible the limit of vanishingly small right-hand-side of Eq. (5), provide motivation for the possibility [5, 7] that in quantum gravity there be a T_{obs}-dependent intrinsic uncertainty in any measurement that monitors a distance D for a time T_{obs}. Gravitation forces us to renounce to the idealization of infinitely-massive devices and this in turn forces us to deal with the element of decoherence encoded in the fact that measurements requiring longer times of observation are intrinsically/fundamentally affected by larger quantum uncertainty.

It is important to realize that this element of decoherence found in the analysis of the measurability of distances comes simply from combining elements of quantum mechanics with elements of classical gravity. As it stands it is not to be interpreted as a genuine quantum-gravity effect, but of course this argument based on the Salecker-Wigner limit provides motivation for the exploration of the possibility that quantum gravity might accommodate this type of decoherence mechanism at the fundamental level. In the analysis of the Salecker-Wigner setup the T_{obs} dependence is not introduced at the fundamental level; it is a derived property emerging from the postulates of gravitation and quantum mechanics. However, it is plausible that quantum gravity, as a fundamental theory of space-time, might accommodate this type of bound at the fundamental level (*e.g.*, among its postulates or as a straightforward consequence of the correct short-distance picture of space-time). It is through this (plausible, but, of course, not self-evident) argument that the Salecker-Wigner limit provides additional motivation for the interferometric studies discussed in Section 2. The element of decoherence encoded in the stochastic models of fuzzy space-time is quite consistent with the type of decoherence mechanism suggested by the analysis of the Salecker-Wigner measurement procedure. One could see the Wheeler-Hawking picture of an "active" quantum-gravity vacuum and the measurability bound suggested by the analysis of the Salecker-Wigner measurement procedure as independent arguments in support of distance fuzziness of the type here reviewed in Section 2. Of course, the intuition associated to the arguments of Wheeler, Hawking and followers is more fundamental and has wider significance, but the analysis of the Salecker-Wigner measurement procedure has the advantage of allowing to develop (however heuristic) arguments in support of one or another form of fuzziness, whereas the lack of explicit models providing a satisfactory implementation of the Wheeler-Hawking intuition forces one to adopt parametrizations as general as the one in Eq. (1). From this point of view, arguments based on the Salecker-Wigner measurement procedure can play a role similar to the one played by the arguments based on quantum-gravity-induced deformations of dispersion relations, which, as already mentioned in Section 2, can also be used [4] to support specific corresponding models of fuzziness (values of β) within the class of models parametrized in Eq. (1).

Let me devote the rest of this section to some of the arguments based on analyses of the Salecker-Wigner measurement procedure that provide support for one or another form of distance fuzziness. As observed in Refs. [3, 4] a particular value of β can be motivated by arguing in favour of a corresponding explicit form of the T_{obs} dependence of the bound on the measurability of distances. Let me here emphasize that the robust part of the quantum-gravity argument based on the analysis of the Salecker-Wigner measurement procedure only allows one to conclude that the T_{obs} dependence cannot be eliminated, and this is not sufficient for obtaining an explicit prediction for the T_{obs}-dependent measurability bound. A robust derivation of such an explicit formula would require one to have available the correct quantum gravity and derive from it whatever quantity turns out to play effectively the role of the minimum quantum-gravity-allowed value of $M_b^{-1} + M_d^{-1}$. Since quantum gravity is not available to us, we can only attempt intuitive/heuristic answers to questions such as: should quantum gravity host such an effective minimum value of $M_b^{-1} + M_d^{-1}$? how small

could this effective minimum value of $M_b^{-1} + M_d^{-1}$ be? could this minimum value depend on T_{obs}? could it depend on the distance scales being probed? This questions are discussed in detail in Refs. [4, 5, 7, 20]. For the objectives of the present Letter it is important to discuss explicitly in which sense one is seeking answers to these questions. In seeking these answers one is trying to get an intuition for the fundamental conceptual structure of quantum gravity, and therefore one considers the measurement procedure from a viewpoint that would seem appropriate for the definition of distances possibly as short as the Planck length. [Some authors (quite reasonably) would also expect quantum gravity to accommodate some sort of operative definition of space-time based on a network of material-particle (possibly minute clocks) worldlines.] It is from these viewpoints that one must approach the questions raised by analyses of the Salecker-Wigner setup. As it will be discussed in the next three sections, one is led to very naive conclusions by adopting instead a conventional viewpoint based on the intuition that comes from present-day rudimentary (from a Planck-length perspective) experimental setups. The logic of the line of research started by the work of Salecker and Wigner is the one of applying the language/structures we ordinarily use in physical contexts we do understand to contexts that instead seem to lie in the realm of quantum gravity, hoping that this might guide us toward some features of the correct quantum gravity. We already know the answers to the above questions within ordinary gravitation and quantum mechanics, and therefore an exercise such as the one reported in Ref. [1] could not possibly teach us anything. It is instead at least plausible that we get a glimpse of a true property of quantum gravity by exploring the consequences of removing one of the elements of the ordinary conceptual structure of quantum mechanics. The Salecker-Wigner study (just like the Bohr-Rosenfeld analysis) suggests that among these conceptual elements of quantum mechanics the one that is most likely (although there are of course no guarantees) to succumb to the unification of gravitation and quantum mechanics is the requirement for devices to be treated as classical. Removal of this requirement appears to guide us toward some candidate properties of quantum gravity (not of the ordinary laws of gravitation and quantum mechanics!), which we can then hope to test directly in the laboratory (as in some cases is actually possible [3, 4]).

I shall go back to these important points in the next three sections, but before I do that let me just briefly summarize the outcome of two simple attempts to extract quantum-gravity intuition from the conceptual framework set up by Salecker and Wigner. One of these approaches I have developed in Refs. [4, 5, 7]. It is based on the simple observation that if in quantum gravity the effective minimum value of $M_b^{-1} + M_d^{-1}$ was T_{obs}-independent and δD-independent, say $min(M_b^{-1} + M_d^{-1}) = [max(M^*)]^{-1} \equiv cL_{QG}/\hbar$, we would then get a bound on the measurability of distances which goes like $\sqrt{T_{obs}}$

$$\delta D \geq \sqrt{\frac{\hbar T_{obs}}{2\, max(M^*)}} \equiv \sqrt{\frac{cT_{obs}L_{QG}}{2}} \ , \qquad (6)$$

and would therefore be suggestive [3, 4, 20] of random-walk stochastic processes. I also observed that, if this effective $max(M^*)$ of quantum gravity could still be interpreted as some maximum mass of the devices used in the measurement procedure, the value of $max(M^*)$ could be bound by the observation that in order to allow the measurement procedure to be performed these devices should at least be light enough not to turn into black holes. This allows one to trade [4, 5, 7] the effective mass scale $max(M^*)$ for an effective length scale s^* which would be the maximum effective size[11] allowed in quantum gravity for the individual

[11]From the viewpoint clarified above it is natural to envision that this length scale s^* would be a fundamental scale of quantum gravity. Instead of introducing a dedicated scale for it one could be tempted to consider the possibility that s^* be identified with the only known quantum-gravity scale L_p, even though this would render somewhat daring the possible interpretation of s^* as maximum size of the devices involved

devices partecipating to the measurement procedure:

$$\delta D \geq \sqrt{\frac{L_p^2 \, c \, T_{obs}}{s^*}} \ . \tag{7}$$

[Of course, this whole exercise of trading $max(M^*)$ for s^* only serves the purpose of giving an alternative intuition for the new length scale L_{QG}, which can now be seen as related to some effective maximum size of devices s^* by the equation $L_{QG} \equiv L_p^2/s^*$.]

Another approach to the derivation of a candidate quantum-gravity bound on the measurability of distances from an analysis of the Salecker-Wigner measurement procedure has been developed by Ng and Van Dam [6]. These authors took a somewhat different definition of measurability bound [4, 5, 7] and they also advocated a certain classical-gravity approach to the estimate of $max(M^*)$. The end result was

$$\delta D \geq (L_p^2 \, c \, T_{obs})^{1/3} \ . \tag{8}$$

In Ref. [3, 4] it was observed that a T_{obs}-dependence of the type in Eq. (8) would be suggestive of the stochastic space-time model with $\beta = 5/6$.

It is interesting to observe [6, 5] that relations such as (7) and (8) can take the form of D-dependent bounds on the measurability of D by observing that $D \sim T_{obs}$ in typical measurement setups. The bounds would be $\delta D \geq \sqrt{D L_{QG}} \equiv \sqrt{D L_p^2/s^*}$ and $\delta D \geq (D L_p^2)^{1/3}$ respectively for (7) and (8).

5 ON THE SALECKER-WIGNER CLOCK

As manifest in the brief review provided in the previous two sections, the Salecker-Wigner limit and the associated intuition concerning quantum properties of space-time is based on an in-principle analysis of the measurement of distances, with emphasis on the nature of the devices used in the measurement procedure. Accordingly, the measurement procedure is only schematically described and only from a conceptual point of view. The devices used in the measurement procedure are also only considered from the point of view of the role that they play in the conceptual structure of the measurement procedure. For example (an example which is relevant for some of the incorrect conclusions drawn in Ref. [1]), the Salecker-Wigner "clock" is not simply a timing device, but it is to be intended as the network of instruments needed for the "clock" to play its role in the measurement procedure (*e.g.* instruments needed to trigger the transfer of information from the clock to the rest of the network of devices that form the apparatus or instruments needed to affect the position of the clock in ways needed by the measurement procedure). This was already very clearly explained in the early works [2] by Salecker and Wigner, which in various points state that the relevant idealized clocks are, for example, capable of sending and receiving signals (they are therefore composite devices including at least a clock, a transmitter and a receiver). It is in this sense that Salecker and Wigner [2] consider the clock. As mentioned, they also had in mind a rough picture in which space-time could be in principle operatively defined by a network of such free-falling clocks, providing a material reference system [32]. If this (as it might well be) was the proper way to obtain an operative definition of space-time, one would obviously be led to consider each of the clocks in the network to be extremely small and light. In general a rather natural intuition is that the ideal clocks to be used in the measurement

in the measurement. In a sense more precisely discussed in Refs. [3, 4, 20], this identification $s^* \equiv L_p$ is already ruled out by the same Caltech data mentioned above [29].

of a gravitational observable should be very light, in order not to the disturb the observed quantity. The same of course holds for all other devices used in a gravitational measurement. How light all these devices should be might depend on the intended scale/sensitivity at which the measurement is performed; for the operative definition of Planckian distances one would expect that, since even tiny disturbances would spoil the measurement, this ideal devices should be very light, but the correct quantum gravity would be needed for a definite answer.

The criticism of the Salecker-Wigner limit expressed in Ref. [1], was essentially based on two observations. One of the observations, which I will address in the next two sections, was based on the idea that it might be possible to avoid the $\sqrt{T_{obs}}$ dependence characteristic of the Salecker-Wigner limit. The other observation, which I want to address in this section, was based on the fact that the data already available from the *Caltech 40-meter interferometer* (the same here used in Section 2 to set bounds on simple models of fuzziness) imply that the effective clock mass to be used in the Salecker-Wigner formula would have to be larger than 3 grams, which the authors of Ref. [1] felt to be to high a mass to be believable as a candidate mass of fundamental clocks in Nature. As underlined by the choice of observing [1] that the 3-gram bound is comparable to masses of wristwatch components, this comment and criticism comes from taking literally the Salecker-Wigner clock as a somewhat ordinary timing device. This misses completely the point emphasized in the brief review I have given above, *i.e.* that the role of the effective Salecker-Wigner clock mass cannot be taken literally as the mass of an ordinary timing device: it is a more fundamental effective mass scale characterizing the devices being used (as clearly indicated by the fact that Salecker and Wigner attribute to their conceptualization of a "clock" the capability to transmit, receive and process signals). One must also consider that this idealized clock was conceived as a device needed for a proper operative definition of Planck-scale distances, and therefore there is little to be gained from the intuition of wristwatches and other ordinary timing devices. The comment on the 3-gram bound given in Ref. [1] also fails to take into account the arguments, which had already appeared in the literature [4, 5, 7] and have been here reviewed in Section 4, concerning the need to interpret the effective mass of the idealized Salecker-Wigner clock as a fundamental but not necessarily universal property of quantum gravity, possibly depending on the type of length scales involved/probed in the experiment (as argued above for the associated effective scale $max(M^*)$). For experiments involving distance scales as large as 40 meters, the result $max(M^*) > 3grams$ seems perfectly consistent[12] with the idea that there should be some absolute bound on $max(M^*)$ in any given quantum-gravity experimental setup. If experiments had given a positive result (say, $max(M^*) \sim 2grams$) it would have not upset anything else we know abut the physical world (only the most sensitive interferometers would be sensitive to the effects of a Salecker-Wigner limit with $max(M^*) \sim 2grams$), but at the same time the fact that it was instead found that $max(M^*) > 3grams$ in experiments involving distance scales as large as 40 meters should not surprise us nor is it inconsistent with the arguments put forward by Salecker and Wigner and followers. Because of the present very early stage of development of quantum gravity, we are at the same time looking for the value (if any!) of $max(M^*)$ and looking for an understanding of what is the correct interpretation and the true physical origin of such a bound on $max(M^*)$ in a quantum gravity that would accommodate it at some fundamental level.

The points I discussed in this section also clarify, within an explicit example, the sense in which the logic adopted in Ref. [1] is inadequate for the analysis of the conceptual framework

[12]Perhaps a bound of the type $max(M^*) > 3grams$ would instead be surprising if we had found it in experiments defining Planckian distances in the spirit of the type of networks of worldlines considered by Salecker and Wigner (experiments which of course are extremely far in the future if not impossible in principle). Actually, it is quite daring to trust our feeling of "surprise" when venturing so far from our present-day intuition: along the way to the Planck scale we might be forced to change completely our intuition about the natural world. For example, on the subject of timing devices here of relevance the interplay between gravitation and quantum mechanics might even provide us new types of timing devices. (One attempt to construct such new tools is discussed in Ref. [36] and some of the references therein.)

set up by Salecker and Wigner. In Ref. [1] the whole discussion of the "Salecker-Wigner clock" remained strictly within the confines of the intuition and the logic of ordinary gravitation and quantum mechanics, where we have nothing to learn. The conceptual framework set up by Salecker and Wigner instead treats the clock in a way which, in as much as it renounces to the idealization of a classical clock, encodes one plausible departure from the ordinary laws of quantum mechanics that could be induced by the process of unification of gravitation with quantum mechanics.

6 ON THE USE OF A POTENTIAL WELL TO REDUCE CLOCK-INDUCED UNCERTAINTY

In Ref. [1] the work of Salecker and Wigner was also criticized by arguing that it would be inappropriate to treat the clock as freely moving, as effectively done in the derivation of the Salecker-Wigner limit. We were reminded in Ref. [1] of the fact that for a clock appropriately bound (say, by some ideal springs) to another object in its vicinity the uncertainty in the position of the clock with respect to that object would not increase with time, unlike the case of a free clock.

This observation completely misses the point of the Salecker-Wigner limit. The uncertainty responsible for the Salecker-Wigner limit comes from the uncertainty in the relative position between the clock and the two bodies whose distance is being measured (say, the distance between the clock and the center of mass of the system composed of the two bodies whose distance is being measured). By binding in an harmonic potential the clock and an external body one would not affect the nature of the Salecker-Wigner analysis. The position of the clock (or, say, the center of mass of the system composed of the clock and the external body) relative to the two bodies whose distance is being measured (or, say, relative to the center of mass of the system composed of the two bodies whose distance is being measured) is still a free coordinate whose uncertainty contributes directly to the uncertainty in our measurement of distance. The uncertainty in this free coordinate will spread according to the formula

$$\delta x \geq \sqrt{\frac{\hbar T_{obs}}{2} \left(\frac{1}{M_b} + \frac{1}{M_c + M_{extra}} \right)} \,, \tag{9}$$

where M_{extra} is the mass of the mentioned external body. The T_{obs} dependence necessary for all the significant implications of the Salecker-Wigner analysis is still with us. Contrary to the claim made in Ref. [1], by binding in an harmonic potential the clock and an external body, one does not truly eliminate the T_{obs}-dependent uncertainty: one simply trades one source of T_{obs}-dependent uncertainty for another essentially equivalent source. This simply provides one more example of intuition for the $max(M^*)$ discussed in the preceding sections (and in Refs. [4, 5, 7]), which in this context would be identified with the inverse of $min\{1/M_b + [1/(M_c + M_{extra})]\}$. [In any case, as explained above, M^* would plausibly not only reflect the properties of the devices used for timing but of the whole set of devices needed for the measurement of distances.]

Whether or not there is a spring binding the clock and an external body, as a result of the analysis of the Salecker-Wigner measurement procedure we are still left with the intuition that some fundamental (although perhaps dependent on the distance scale which is to be measured [4]) value for $max(M^*)$ might be a prediction of quantum gravity and we are still left wondering how large this $max(M^*)$ could be. Perhaps when measuring large distances with relatively low accuracy quantum gravity might allow us to take rather large M^* (which, if so desired, one might effectively describe in the language of Ref. [1] as the possibility to introduce a rather heavy external body to be "attached" to the clock),

but as shorter distances are probed the disturbance of a large M^* (or the introduction of heavy bodies to which the clock would be attached) must eventually become unacceptable. This is certainly plausible, but what could be the value of $max(M^*)$ for measurements at a given distance scale? The correct answer of course requires full quantum gravity (because it must reflect the way in which the operative definition of distances in codified in quantum gravity), but we can try to gain some insight by pushing further the experimental bounds on $max(M^*)$. Even more complicated at the conceptual level is the search of an analog of M^* in attempts to operatively define a tight (perhaps Planck-length tight) network of geodesic (world) lines, in the spirit of "material reference systems" [32] and of some of the comments found in the work of Salecker and Wigner [2]. Is such a task to be required of quantum gravity? How large/heavy could the clocks suitable for this task be? Wouldn't it be paradoxical to consider the possibility of attaching these free-falling clocks to some external bodies? As already emphasized in Refs. [4, 5, 7] there are several quite overwhelming open issues, but it seems unlikely that we could gain some insight by extrapolating *ad infinitum* (as done in Ref. [1]) from the intuition of measurement-analysis ideas applicable to rudimentary present-day experimental setups.

Before closing this section let me comment on another scenario that some readers might be tempted to consider as a modification of the potential-well proposal put forward in Ref. [1]. One might envisage using some springs to connect the clock to one of the bodies (say body A) whose distance is being measured, rather than connecting the clock to an external body. This would assure that the uncertainty in relative position between the clock and that body A does not increase with time, but it is easy to verify that the disturbance that this setup would introduce is of the same magnitude as the uncertainty it eliminates. In fact, the system composed of the clock and body A would be free. Essentially the uncertainty in the initial momentum and position of the clock relative to the second body (body B) would now be transferred to the body A "through the springs". This would introduce an uncertain disturbance to the distance between body A and body B that is being measured, and the disturbance is of course just of the same magnitude as the uncertainty contribution arising in the original Salecker-Wigner setup. In addition, each time the (Salecker-Wigner-type) clock emits a signal the corresponding uncertain recoil would be transmitted through the spring to the body A.

7 ON THE POSSIBILITY OF A FUNDAMENTALLY CLASSICAL CLOCK

As an alternative possibility to eliminate the $\sqrt{T_{obs}}$ dependence present in the Salecker-Wigner limit, in Ref. [1] we are reminded of the fact that ordinary clocks are immerged in a (thermal or otherwise) environment that induces "wave-function collapse". In fact, to extremely good approximation these clocks behave classically.

Again this is a correct intuition derived from experience with rudimentary (from a Planck-scale viewpoint) experimental setups, which however (like the other points argued in Ref. [1]) appears to be incorrectly applied to the conceptual framework considered by Salecker and Wigner. While "environment-collapsed" clocks (and other environment-collapsed devices) could be natural in ordinary contexts, it seems worth exploring the idea that quantum gravity, as a truly fundamental theory of space and time, would not resort (at an in-principle level) to collapse-inducing environments for the operative definition of distances. In any case, this is the expectation concerning quantum gravity that is being explored through the relevant Salecker-Wigner-motivated research line. It also seems that quantum gravity, having to incorporate an operative definition of distances applicable even in the Planck regime, would have some difficulties introducing at a fundamental level the use of environments to collapse the wave function of devices. How would such an environment look like for the case in which

one is operatively defining a nearly-Planckian distance? (and which type of environment would be suitable for the operative definition of a Planck-length-tight network of world lines? how would such an environment be introduced in the operative definition of a material reference system?)

Concerning the possibility of a fundamentally classical clock in Ref. [1] the reader also finds what appears to be a genuinely incorrect statement (not another example of ordinary intuition inappropriately applied to the forward-looking framework set up by Salecker and Wigner, but simply a case of incorrect analysis). In fact, Ref. [1] appears to suggest that the interactions among the components of even a perfectly/ideally isolated clock might induce classicality of the position of the center of mass of the clock, which is the physical quantity whose quantum properties lead to the Salecker-Wigner limit. While the interactions among the components should lead to the emergence of some classical variables (*e.g.*, the variable that keeps track of time), if the clock is ideally isolated interactions among its components should not have any effect on the quantum properties of the position of the center of mass of the clock. [This is certainly the case for some of the explicit examples of “toy clocks” considered by Salecker and Wigner, one of which is only composed of three free-falling particles!]

8 CLOSING REMARKS

From a conceptual viewpoint the analysis reported in Ref. [1] can be divided in two parts. In one part a set of questions was raised and in the other part tentative answers to these questions were given. As this Letter emphasized, some of the questions considered in Ref. [1] are indeed the most fundamental questions facing research based on the Salecker-Wigner limit. However, all of these questions had already been raised in previous literature (see, *e.g.*, Refs. [4, 5, 7]). These questions have been here compactly phrased as: should quantum gravity predict a $max(M^*)$ and could this be interpreted as the maximum acceptable mass of one or more devices? how large could $max(M^*)$ be? should $max(M^*)$ depend on the distance scales being probed? should the idealization of a classical clock survive the transition from ordinary quantum mechanics to quantum gravity?

While the questions considered are just the right ones, the answers given in Ref. [1] are incorrect. In this note I have tried to clarify how those answers are the result of inappropriately applying the intuition of rudimentary (from a Planck-scale viewpoint) measurement analysis to the forward-looking framework set up by Salecker and Wigner. The debate on the Salecker-Wigner limit must of course continue until the above-mentioned outstanding open questions get settled, but (if the objective remains the one of getting ideas on plausible quantum-gravity effects) the only possibly fruitful way to approach this problem is the one of seeking the answers within the same forward-looking framework where the questions arose. Nothing more than what we already know can be learned by assuming that the laws of ordinary gravitation and quantum mechanics remain unaltered all the way down to the Planck regime. As emphasized here, the logic of the line of research started by the work of Salecker and Wigner is the one of applying the language/structures we ordinarily use in those physical contexts that we do understand to contexts that instead would naturally lie in the realm of quantum gravity, and then exploring the consequences of removing one of the elements of the ordinary conceptual structure of quantum mechanics. The Salecker-Wigner study (just like the Bohr-Rosenfeld analysis) suggests that among these conceptual elements of quantum mechanics the one that is most likely to succumb to the unification of gravitation and quantum mechanics is the requirement for devices to be treated as classical. Removal of this requirement appears to guide us toward some candidate properties of quantum gravity (not of the ordinary laws of gravitation and quantum mechanics!), which we can then hope to test directly in the laboratory (as in some cases is actually possible [3, 4]).

Quite aside from the subject of open issues in the study of the Salecker-Wigner limit, I have also emphasized in this Letter that, contrary to the impression one gets from reading Ref. [1], there is substantial motivation for the phenomenological programme of interferometric studies [3, 4] of distance fuzziness here reviewed in Section 2, independently of the Salecker-Wigner limit (and independently of the fact that, as clarified above, the validity of this limit has not been seriously questioned). As discussed in Section 2 (and discussed in greater detail in Ref. [4, 20]), the general motivation for that phenomenological programme comes from a long tradition of ideas (developing independently of the ideas related to the Salecker-Wigner limit) on foamy/fuzzy space-time, and also comes from more recent work [18, 14, 15, 16, 19] on the possibility that quantum-gravity might induce a deformation of the dispersion relation that characterizes the propagation of the massless particles used as space-time probes in the operative definition of distances. It is actually quite important that this interferometry-based phenomenological programme, as well as other recently-proposed quantum-gravity-motivated phenomenological programmes [20, 26, 27, 14, 37, 38], be pursued quite aggressively, since the lack of experimental input has been the most important obstacle [39] in these many years of research on quantum gravity.

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